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ABSTRACT

Sixteen years of typhoon data were studied, in an effort to develop a technique for forecasting tropical cyclone intensity changes in the Northwestern Pacific. The data base provided average changes for 24 and 48 hour periods along with the average duration of each phase (intensifying and dissipating). Further study revealed that the upper-level outflow patterns provide a means to adjust these average changes so a more realistic forecast could be generated for the individual storms. Forecasts were further improved by studying how land and other environmental features effect the life cycle of tropical cyclones.

Results from the research were compiled and incorporated into a series of flow charts. These charts were created to enable individuals to quickly determine future intensities of cyclones given the storm's history and a current satellite picture.

FORECASTING 24 AND 48 HOUR INTENSITY CHANGES,

FOR NORTHWESTERN PACIFIC TROPICAL CYCLONES,

USING SATELLITE IMAGERY

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
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OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

OF METEOROLOGY

MAY 1989

By

Richard W. Hartman

Thesis Committee:

Thomas A. Schroeder, Chairman
Yi-Leng Chen
Bin Wang

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Masters of Science in Meteorology.

THESIS COMMITTEE

Chairman

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Sixteen years of typhoon data were studied, in an effort to develop a technique for forecasting tropical cyclone intensity changes in the Northwestern Pacific. The data base provided average changes for 24 and 48 hour periods along with the average duration of each phase (intensifying and dissipating). Further study revealed that the upper-level outflow patterns provide a means to adjust these average changes so a more realistic forecast could be generated for the individual storms. Forecasts were further improved by studying how land and other environmental features effect the life cycle of tropical cyclones.

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(EMK)

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LIST OF ABBREVIATIONS

DMSP	Defense Meteorological Satellite Program
ET	Extratropical
GARP	Global Atmospheric Research Program
Kts	Knots
MACR	Military Airlift Command Regulation
mb	Millibar
MSLP	Minimum Sea-Level Pressure
SD	Standard Deviation
SS	Sample Size
SST	Sea Surface Temperature
ST	Super Typhoon
T	Typhoon
TC	Tropical Cyclone
TS	Tropical Storm
TUTT	Tropical Upper-Tropospheric Trough
Z	Zulu Time

CHAPTER 1

INTRODUCTION

Tropical cyclones are a threat to shipping, air traffic and coastal habitation. Until recently, information was too sparse for effective study of these systems. In the last several decades ship, island and buoy reports have been compiled and evaluated.

In addition, since World War II, weather radar, weather reconnaissance aircraft and orbiting weather satellites have become available. Through these new and different platforms we have developed an excellent data base for tropical cyclone research in the Western Pacific.

The purpose of this paper is to review the different phases of tropical cyclone development and then to develop a climatology for forecasting intensity changes for 24 and 48 hour periods, in the Western Pacific Ocean, using satellite imagery. The climatology will help to determine the average intensity changes. The satellite imagery will then help to fine tune the process by providing current information for each situation. This will allow forecasts to be tailored for individual storms, thereby, reducing error.

CHAPTER 2

INTENSITY ANALYSIS USING SATELLITE IMAGERY

Sadler (1963) implied that the cloud signature, induced by the swirling winds, is a good indicator of storm intensity. Importance is placed on the shape the cloud vortex assumes and not the amount of clouds present. Dvorak (1975) researched this idea and developed a method for analyzing tropical cyclone intensity using only satellite imagery. In most cases, the storm will begin as an organized mass of thunderstorms and eventually evolve into a comma-shaped pattern (Fig. 1). Cloud features in this pattern are broken down into two categories:

1. Central features (CF): As the name implies, those features which are characteristic of the central part of the storm (ie. central dense overcast or the eye).
2. Banding features (BF): Cloud bands which form around the central features.

The intensity is mainly determined by the central features with small adjustments made with the appearance of the banding features. Examples of storm patterns using both are given in Fig. 2. This figure also shows the code number that Dvorak assigned to the particular patterns in order to indicate its intensity. Table 1 converts the code to estimated wind speeds and minimum sea-level pressure (MSLP).

In addition to analyzing the current situation, Dvorak went one step further by attempting a 24 hour intensity forecast. He found that, given the proper environment, a storm will increase/decrease by one T# (for definition of T#, see Dvorak, 1975) per day. The environment favorable for these processes is marked by features in the storm and in the surrounding environment. Some signs of intensification are:

1. Cloud pattern appears as a bright, sharply defined, comma shape.

2. Central features exhibit deep convection or dense, solid overcast.

3. Comma or peripheral clouds, equatorward or in the direction of vortex movement, being strongly convective.

4. Cirrus spreading out over three or more quadrants.

A weakening storm will show:

1. A less well defined boundary (ragged eye or periphery).

2. Less smoothness in central dense overcast.

3. The cloud pattern becoming more circular.

The environmental features which can cause a tropical cyclone to decay are (Dvorak, 1975) are:

1. Land (frictional dissipation).

2. Cyclone moving into a stratocumulus field.

3. Storm outflow showing signs of weakening (loss of an outflow channel or reduced activity in the channel).

4. Apparent blocking (This is recognizable when cloud systems become elongated and perpendicular to cyclone movement. Convection will also appear suppressed).

CHAPTER 3

DEVELOPING TROPICAL CYCLONE CLIMATOLOGY

3.1 Background on Data Set

Using the same idea as Dvorak, I hope to develop a procedure in which 24 and 48 hour intensity forecasts can be made for tropical cyclones in the Northwestern Pacific. To accomplish this task, a study had to be made on typhoon activity, in that region, over an extended period of time. For this, I used a data set provided by the Joint Typhoon Warning Center (JTWC). The JTWC located on Guam, monitors and forecasts tropical cyclone motion in the Western Pacific Ocean. Each year, they compile information on each cyclone that occurred in their area of responsibility and publish it in their Annual Tropical Cyclone Report. A section is dedicated to each storm to include a condensed discussion of the synoptic situation, in which the storm evolved, and a satellite image of the storm. Also included is a gridded map (Fig. 3) showing the storm track in six hourly intervals (U. S. FWC/JTWC, 1972-87). I used 16 years (1972-87) of data in this study.

Since it is desirable to develop a climatology of the storm life cycle from inception to dissipation, the storm track charts were the perfect data source. To reduce possible errors due to late storm detection and evaluation,

I began each case at the point the cyclone first reached tropical storm strength (greater than 33 kts) (First Weather Wing, 1979). From this point, wind speeds were recorded for consecutive fixes at intervals of 24 hours until the cyclone dissipated. Wind speeds were converted into H#'s for ease in manipulation and display (Table 2).

3.2 Climatology of Intensity Changes

The next step was two-fold. By using this raw data, I studied the rate at which a storm develops or weakens in 24 and 48 hour periods. I also observed the duration of the intensification and dissipation phases. This latter observation will be a useful tool in determining when a storm will reach its maximum intensity and/or when it will dissipate.

Additionally, I wanted to examine the role land played in my analysis. To determine this, the previous test was repeated using only those storms which were not affected by land. This set is labeled land-filtered. Conversely, a land-inclusive set was developed from the remaining storms.

Contact with or affected by land can be vague when dealing with tropical cyclones. Therefore, I studied several storms to find out how close they had to be to land before they showed signs of weakening (ie. decrease in wind speed). On the average, one degree latitude was a fair approximation but to be on the more conservative side, two

degrees latitude from the storm center was chosen. In terms of land mass size that could be considered an effective obstruction, an area on the magnitude of Luzon was used. The smaller, isolated islands were neglected because they lacked sufficient land area and topography to generate significant frictional dissipation.

Table 3 shows the mean and standard deviations for each data set. Initially, the results of the intensity change categories appeared similar with each set indicating approximately 15 kt increases/decreases per 24 hours. However, there were slight differences. As would be expected, the land-filtered set had higher mean values for the intensifying phase and lower values for the dissipation stage than the land-inclusive set. In an effort to determine if the difference was based on the samples tested or whether there truly would be significant change given more data (ie. land having a significant impact on statistical tests), a Student T-test was accomplished.

3.3 Student T-Test

The T-test takes two independent samples and by using their means and variances, determines if the sample means are the same or different.

In this case, the two samples are the land-inclusive and land-filtered typhoons sets. The question that needs to be answered is whether land has an effect on the intensity

change of the storms and/or the amount of consecutive intensity trend days (Panofsky and Brier, 1958). We begin with two hypotheses:

H0: Land has no effect on intensity.

H1: Land has an effect on intensity.

The T-test can accept or reject only the H0 hypothesis. If H0 is not rejected the T-test is of little use.

After completing the statistical work, the results for the intensity categories indicated that the H0 hypothesis cannot be rejected. At this point, it should be noted that in many of the landfall cases, on the Asian continent, wind data was discontinued because the storm was assumed dead. Therefore, a majority of the land effects, contained in my data, were due only to islands or brushes with the China coast. This result indicates that the Pacific islands probably have a negligible effect on tropical cyclones. The only exception is the Philippine Islands which will be dealt with later in the paper.

The consecutive days test did show a difference which allows us to reject the H0 hypothesis for these categories. We can now be confident that land does effect the consecutive number of days in which a storm intensifies or weakens. This observation makes sense in that the frictional dissipation of land can act to slow the cyclones development.

3.4 The Outflow Theory

To add more confidence to this statistical study, the mode for each category and data set was plotted as bar graphs (Figs. 4, 5, and 6). The most frequently occurring intervals of change match very well with the means in each case. The distributions also compare well with the standard deviations. In addition, notice that the graphs are all skewed, bell-shaped curves. This indicates that although the majority of storms fell into the average area, there were several cyclones which intensified or dissipated at an above average rate (greater than 15 kts/24 hours).

To better understand these changes, I explored a theory which studies each tropical cyclone individually to see why they deviate from the average. Sadler (1976) theorized that the rate of storm intensification could be due to the interaction of the upper-level outflow of the tropical cyclone with the large scale environmental flow. Fig. 7 provides examples of this interaction. The first panel (a) illustrates the climatological upper-air flow for the early half of the typhoon season (Jun-Sep). The storm outflow is super-imposed on this diagram to show the amount of shear that most quadrants of the storm experience, thus greatly inhibiting development. The remaining two diagrams show a channel into the westerlies to the north of outflow, created by a mid-latitude trough (Oct-Dec) (b) or the TUTT (c), in

addition to the already established channel into the easterlies to its south. These latter situations reduce the vertical shear over the storm and create a more efficient outflow of mass and heat. This action results in a rapid lowering of the storm's central pressure, allowing for an increased rate of intensification (Sadler, 1976).

Chen and Gray (1985) expanded on Sadler's outflow theory by focusing on the significance of the number of outflow channels and their orientation. The orientation of the channels is determined primarily by the position of the upper-level, synoptic scale anticyclone in relation to the outflow region of the tropical cyclone. Three main patterns are examined: single, double and no-outflow (neutral). These three basic patterns were then broken down into several sub-categories (Fig.8) to provide a complete set of examples for pattern comparison and study with the actual environment.

The First GARP Global Experiment (FGGE) year provided an excellent data source for tropical cyclone activity around the world. Satellite imagery was used to determine the type of outflow channel occurring while the FGGE data provided the wind speeds. The results of the comparison are plotted in Fig. 9. The significant differences (10-15 kts/6 hours) occurred between the double, single polar and single equatorial categories but not within a particular category (ex. Spc and Spw are within the same category). As would be

expected, the double channel configuration provided the strongest intensity changes (33 kts/6 hours) with single equatorial (25-27 kts/6 hours) and single polar (18-20 kts/6 hours) following in suit. The equatorial directed flow was stronger than the polar outflow because of the influence of the strong, near-equatorial, easterly winds which enhances the mass divergence aloft.

To be sure their test was not biased, I examined seven years (1980-86) of storm data for the Northwestern Pacific using GMS imagery. Only typhoons were examined and only after tropical storm strength was achieved. This provided a good sample of outflow patterns which were more clearly distinguishable than they would be in the earlier phases of storm development. I quickly found out; however, that the patterns aren't always easily discernible but once established the pattern usually remains consistent through the intensification phase of the storm.

For this study, the categories of outflow patterns were reduced to single equatorial, single polar, double and neutral patterns (eliminating sub-categories). The time interval chosen was 24 hours. The purpose of this was to see if these patterns would be good indicators for rapid intensification. The results in Fig. 10 verify that the double outflow pattern is, in fact, more effective at intensifying a tropical cyclone than the other patterns. What was surprising was that the neutral pattern was also a

good indicator of rapid storm growth. Chen and Gray (1985) attribute this to upper-level winds that are not in contact with the storm's outflow. Therefore, the shearing effect is removed, allowing the cyclone to remove its excess mass and heat without impediment.

The strongly divergent, neutral outflow pattern is easily discernible by the lateral cirrus banding around the storm's circumference. Poorly divergent storms have ragged edges and develop very slowly (Chen and Gray, 1985).

The tropical cyclones falling under the non-outflow category, in this study, were comprised of a mixture of the strong and weak divergent patterns as were the other categories tested. This observation emphasizes that the rate of storm intensification is not only due to the amount of outflow channels but more importantly the net amount of divergence aloft which is indicated by the vigor of the outflow.

As noted earlier, this test is subjective and can lead to some differences in test results depending on the judgement of the individual conducting the test. When comparing Figs. 9 and 10, there are notable differences in intensity changes (ie. double outflow from Fig. 9 shows a 33 kt/6 hour change, whereas Fig. 10 shows a 27 kt/24 hour change). These differences stem from the way the tests were conducted. Chen and Gray (1985) studied specific storms around the glove and averaged the wind speeds over a 24 hour

period and only in some cases over several days, whereas my study was restricted to the Northwestern Pacific and examined most of the typhoons between 1980 and 1986. Winds were recorded every six hours for each storm and then each category was averaged over the seven year period.

3.5 Explosive Developers

I defined explosive developers as tropical cyclones that increased by 50 kts or more in a 24 hour period. To isolate these storms, the data were screened from 1972 to 1983, revealing 16 storms which met the above criteria (Table 4). The screening was limited to this period so the intensity changes could be verified with the original aircraft reconnaissance data on hand.

Since aerial reconnaissance is the primary data source, it is helpful to have an understanding of how the aircraft goes about gathering surface wind data in a typhoon. After penetrating the storm at 700 mb, an instrument, called a drop-sonde, is released in or near the eye which transmits the MSLP back to the aircraft. Using an equation, which relates the MSLP to wind speed (Atkinson and Holiday, 1977), the surface winds can be derived from this pressure reading (see Table 4 for the equation). This was the method used to determine the "calculated wind" in Table 4 so the jump in wind speeds could be verified. A second method involves

taking a pressure reading a 1500 feet and extrapolating that to the surface, using a nomogram. The last method is accomplished only if the sea surface is not obscured from the reconnaissance officer's view. If the surface is visible, he can estimate the winds by observing the sea state and comparing it to a pictorial climatology (MACR 105-25, 1985). In many of the instances, the sea state was visible so these wind estimates were recorded. However, according to the winds used in the JTWC's Annual Tropical Cyclone Reports, it appears more confidence was given to the drop-sonde measurements. This comparison shows that no apparent observational error was made in recording the winds since pressure was measured for each instance. Therefore, we are now free to explore the causes of these rapid wind speed changes.

Since vigor of outflow is so important, it helps to examine different atmospheric influences which can enhance these patterns. Fig.11 shows six such cases. These range from opposite hemispheric influences to the mid-latitude troughs or TUTTs interacting with the upper-level, synoptic scale anticyclone or a combination of both. The net result in each case is the tightening of the upper-tropospheric pressure gradient which provides a strong divergent channel for the storm outflow.

Interestingly enough, not all of the explosive developers displayed the double outflow patterns. Some were

single equatorial or neutral but in all cases the upper-level divergence was strong. This was, in part, due to favorable synoptic scale situations as discussed earlier. The 250 mb analysis maps revealed that the explosive development occurred at the time these favorable environmental patterns set up, providing no advanced warning. Therefore, prognostic upper air charts are needed to develop a reliable forecast.

Another forecasting aid is to expect the explosive development to begin 24-48 hours after tropical storm strength is attained. This was determined after studying the life cycle of these cyclones. And it makes sense that the favorable environment will drastically affect the storm early in its development. Further analysis shows that the maximum cyclone strength will be reached at or six hours following the completion of the explosive phase.

3.6 Rapid Dissipators

The other category of storms examined was the rapid dissipators. In this case, these storms were classified as those which weakened at a rate of 35 kts or better in a 24 hour period. Of the 68 storms examined, 45 (66%) dissipated due to land-fall (Asian Continent, Philippines or Japan). Other causes stemmed from late-season storms that rapidly

recurved and went extratropical or just moved over colder water and lost their heat source (Fig. 12).

3.7 The Philippine Islands Situation

Storm interaction with the Philippines was examined in more detail because of the unique situation it created. As a typhoon passed over the country, frictional dissipation would weaken it but then the cyclone would regenerate over the warm waters of the South China Sea. Therefore, I examined the 16 year data set and extracted each storm which was affected by the Philippines. After collecting the storm data, the set was broken down into those storms affected by Luzon and those affected by the other islands in the country (only storms which followed the pattern: decay, intensify, decay were included in the two sub-categories). I treated Luzon separately because of the large mountain chain located on the northern tip of that island. Most of the other islands lack such a feature (Mindanao is the exception, but very few cyclones traveled over this island).

Test results were interesting. The islands had the same effect on the decrease in wind magnitude (approximately 30 kts) but Luzon accomplished the job more rapidly. Additionally, Luzon affected the storms at a greater distance, indicating that the size of the topography plays an important role in determining when a storm will begin dissipation in relation to an obstruction (Table 5).

After weakening, the storms usually re-intensify over the South China Sea because of the high SST and reduced friction. On the average, the storm will intensify 25-30 kts over a period of approximately 30 hours before land-friction from the Asian Continent finally dissipates it.

3.8 Maximum Intensity Indicator

Finally, I examined all the cyclones to see if there was anything that would indicate what its maximum intensity would be. So I examined 65 cyclones which exceeded 100 kts and found that 94% of them had a 35 kt or greater wind increase over a 24 hour period. The average maximum intensity of those cyclones was 128 kts. The test was re-accomplished for a 40 kt or better wind speed increase for the same time period. The results were similar. Therefore, these large wind jumps could be a good indicator for determining the maximum storm intensity.

CHAPTER 4

DISCUSSION OF FORECAST PROCEDURE

This section compiles the research, from the previous chapter, into a flow chart for forecasting the intensity changes of tropical cyclones (Appendix C). This chart is broken down into three parts; the first of which is used to determine whether the tropical cyclone intensity will increase or decrease, with the remaining parts forecasting these changes.

The first section utilizes criteria, provided by Dvorak (1984), which refers to cloud signatures to indicate the intensity trend of the cyclone. The remaining questions refer to the storm's past behavior in order to determine if the cyclone has reached its peak strength.

The storm's past behavior is recorded in Figs. 4-6 and Table 3. Since Fig. 4 represented the average cyclone, I used its data to observe both the mean and mode for the number or days the tropical cyclone increased in intensity to determine when the dissipation phase would begin. The mean duration was 2.69 days which worked out to be approximately 65 hours. The mode also indicated this time period existed between 48 and 72 hours. Therefore, forecasting increasing intensity for 72 hours (unless environmental factors indicated otherwise) after tropical

storm strength is attained is helpful in making the long-range forecasts.

Another help for the extended forecasts are the peak wind indicators. These indicators provide an estimate for when to begin the dissipation phase of the tropical cyclone. In some cases, these indicators and the 72 hour rule will conflict which is when individual experience is heavily relied upon.

Once the intensity trend is determined, the forecast procedure begins. Forecasters first determine whether the cyclone is a slow mover or not. If not, then start with the average increase for tropical cyclones, of 15 kts per 24 hours, as determined in the last chapter. This average is altered depending on the type and strength of the outflow pattern (using Fig. 13). Fig. 13 was accomplished using the results from my outflow pattern survey. Since this survey was representative of the average storms, given an outflow pattern, the range was derived from the mean and standard deviation (with some adjustments).

Explosive developers are a special category of the intensification phase. To predict the onset of this development, prognostic 250 mb charts are necessary because once the favorable environment sets up, the development is instantaneous. This type of behavior is usually characteristic of super typhoons but not limited to them. The bracketed numbers in Fig. 13 should be added to the

average intensity increase for the different types of outflow patterns, if a favorable environment sets up. I derived this number from Chen and Gray's (1985) outflow survey which examined the ideal storms for each pattern.

The weakening phase is similar to the intensification phase in that the average 24 hour change is 15 kts. This is altered only for slow moving storms, those that become extratropical and those that make landfall over the Philippines or the Asian Continent. For these special situation special rates of dissipation were observed from studying the rapid dissipators and cyclone interaction with the Philippine Islands. Storms going extratropical averaged a 30 kt decrease per 24 hours, while storms making landfall average a 40 kt loss for the same time period.

So far only 24 hour forecasts have been discussed. To make the 48 hour forecast, return to the beginning of the flow chart and treat your 24 hour forecast as the observation. After estimating the future position of the tropical cyclone, on the satellite imagery, continue through the procedure as before.

The first 48 hour forecast is difficult. Usually it can be made from persistence using the 24 hour forecast prior to it (ie. if you expect a 15 kt increase for 24 hours, expect the same increase for 48 hours) unless there are other factors (ie. extratropical environment, landfall, etc.) which would indicate otherwise. The exception to this

rule would be when explosive development has already been forecasted. Never expect explosive development twice in one storm. After the first forecast, it will be easier to recognize how the environment will effect this long-range outlook.

The dissipation phase is easier to forecast. Usually, environmental features are present which provide obvious guidance for these forecasts.

CHAPTER 5

SUMMARY AND CONCLUSION

In order to determine the reliability of this forecasting method, a test was conducted to compare this procedure with the JTWC's. Data from the year 1983 was chosen for the test because of the variety of tropical cyclones which occurred and the availability of data.

Data sources included the JTWC's Annual Tropical Cyclone Report for 1983 and GMS imagery. The JTWC publication contains a section on each cyclone, listing the fix position and intensity, along with 24, 48 and 72 hour forecasts. This listing begins with the cyclone's inception and continues through until its demise, at six hourly intervals. The GMS imagery was available for each interval.

The procedure began when the storm reached tropical storm strength. At this point, the storm's center was located on the appropriate satellite picture and the 24 and 48 hour forecasts were made (explosive developers could not be tested for, due to the lack of prognostic upper air charts). These forecasts were then recorded for both methods. The procedure was repeated in 24 hour intervals for the life of the storm. The forecasts were then verified by the "best track" observations.

I found, for 1983, that of the 20 tropical cyclones examined, eight intensified for only 24 consecutive hours

before weakening. A majority of these were influenced by land, formed too far north (greater than 23 degrees north latitude) or formed in the South China Sea. Each of these cases provided sufficient evidence to deviate from the 72 hour rule.

In two other instances, the cyclones moved very slowly and took much longer to reach their peak strength (24-48 hours beyond the original 72 hour forecast). Therefore, the forecast procedure was modified to allow for these deviations.

Wind speed jumps of 35 kts or greater only occurred four times in 1983 and three of those instances were greater than 50 kts. Only one did not verify properly, in that it continued intensifying 24 hours beyond the 50 kt increase.

After concluding the test, the errors for both methods were calculated. This was accomplished by subtracting the "best track" observation from the forecast intensity. The absolute values of these errors were then averaged over the year for each category (ie. 24 and 48 hours) and are displayed in Table 6.

The results indicated that this new technique has merit. To fully appreciate the results, it helps to understand how JTWC makes their forecast. Their forecast procedure consists of two steps. The first step involves making a track forecast. Several computer models are used along with statistical and empirical methods. After

combining all this information, directional and translational speed forecasts are made. After determining the storm's future environment, the intensity changes are then created via analytical and empirical means, being cautious of environmental features which may effect the track (U. S. FWC/JTWC, 1983).

The major differences between the two procedures are found in the track prediction. JTWC, in addition to persistence and climatology, also uses sophisticated computer models. The intensity forecasts are made after the expected positions have been determined. JTWC uses only the Dvorak (1984) forecasting technique (increasing or decreasing cyclones by one T# per day), tempered with individual experience. The disadvantage of this method is that it treats most cyclones the same and offers little guidance for outlooks beyond 24 hours. The climatology developed in this paper is very comprehensive and treats intensity changes differently based on the individual storm and its environment. This is seen by starting with the average change per day (15 kts) and then altering the value based on different criteria (ie. outflow, translational speed, etc.).

During the test, I did have the advantage of knowing in advance, whether the cyclone was a tropical storm, typhoon or super typhoon. This gave me an idea of what the maximum wind speed might be and when to begin the dissipation phase,

However, this advantage should not have had any significant impact on the test results.

In conclusion, I want to emphasize that this method is a guideline created for those with experience in forecasting Western Pacific tropical cyclones. It's advantages are that it is easy to learn, quick to use and economical. The only data sources necessary for this technique are satellite pictures and possibly prognostic 250 mb charts. With these resources and experience, a dependable estimate of tropical cyclone intensity changes out to 48 hours is possible.

Unfortunately, since aircraft reconnaissance is no longer available in the Western Pacific, the accuracy of position and intensity observations will be reduced, According to Martin (1988), this action could result in not only a significant degradation in analysis but also in the short term forecasting of these systems. Fortunately, satellite technology is continuing to advance and will gradually fill this gap. Satellite loopers are already helping forecasters to observe tropical cyclone development and to locate storm centers more accurately. New sensors, such as the Special Sensor Microwave/Imager, currently operating on a DMSP satellite, will be able to see through the cloud decks to the sea surface and provide valuable information on the surface winds surrounding the intense areas of the cyclone (Hollinger et al., 1987). Futuristic improvements on this sensor may allow for determining the

maximum surface wind and a more accurate positioning of the circulation center.

Until further advancements do take place, I believe the technique developed in this paper will add to the current accuracy of tropical cyclone intensity forecasting in the Northwestern Pacific.

APPENDIX A

Table 1.--The empirical relationship between the current intensity number (CI), the maximum mean wind speed (MWS), and the minimum sea-level pressure (MSLP) in tropical cyclones (after Dvorak, 1984)

CI Number	MWS (knots)	MSLP (Atlantic)	MSLP (NW Pacific)
1.0	25		
1.5	25		
2.0	30	1009 mb	1000 mb
2.5	35	1005 mb	997 mb
3.0	45	1000 mb	991 mb
3.5	55	994 mb	984 mb
4.0	65	987 mb	976 mb
4.5	77	979 mb	966 mb
5.0	90	970 mb	954 mb
5.5	102	960 mb	941 mb
6.0	115	948 mb	927 mb
6.5	127	935 mb	914 mb
7.0	140	921 mb	898 mb
7.5	155	906 mb	879 mb
8.0	170	890 mb	858 mb

Table 2.

Relationship between H#'s and knots

H#	Speed (kts)
1	5
2	10
3	15
4	20
5	25
6	30
7	35
8	40
9	45
10	50
11	55
12	60
13	65
14	70
15	75
16	80
17	85
18	90
19	95
20	100
21	105
22	110
23	115
24	120
25	125
26	130
27	135
28	140
29	145
30	150

Table 3.--A collection of the means, standard deviations (SD), and sample sizes (SS) for Figs. 4-6. The 24 and 48 hour categories represent changes in H#'s for the respective time periods. The bracketed numbers represent the values for decreasing intensity while the other numbers are for the increasing phase. The consecutive days category has been listed separately with reference to the intensity changes

Increase/(Decrease)

24 hours

	Total	Land-filtered	Land-inclusive
Mean:	3.44 (3.52)	3.74 (3.40)	3.17 (3.57)
SD:	2.32 (2.56)	2.56 (2.12)	2.12 (2.74)
SS:	885 (682)	454 (234)	413 (441)

48 hours

	Total	Land-filtered	Land-inclusive
Mean:	6.85 (6.30)	7.53 (6.32)	6.24 (6.29)
SD:	3.83 (3.56)	4.03 (3.20)	3.58 (3.67)
SS:	557 (373)	306 (128)	252 (243)

Number of Consecutive Days of Intensity Increase

	Total	Land-filtered	Land-inclusive
Mean:	2.69	2.93	2.51
SD:	1.40	1.38	1.32
SS:	327	154	166

Number of Consecutive Days of Intensity Decrease

	Total	Land-filtered	Land-inclusive
Mean:	2.22	2.21	2.17
SD:	1.43	1.34	1.43
SS:	306	105	204

Table 4.--This is a listing of explosive developers from 1973-83. The wind speed changes, that occurred during the explosive development, which are listed in the JTWC Annual Tropical Cyclone Reports, are compared to calculated winds from the original reconnaissance data

Equation relating wind and pressure: Vm=6.7(1010-Pc)exp 0.644

Vm: Maximum wind velocity
Pc: Central pressure (mb)

Storm Name	Date/Time	Central Pressure	Book Wind	Calculated Wind
ST Billie	14 Jul 73/00Z	983 mb	60 kts	55 kts
	15 Jul 73/00Z	921 mb	115 kts	121 kts
ST Nora	4 Oct 73/12Z	966 mb	75 kts	77 kts
	5 Oct 73/12Z	910 mb	125 kts	130 kts
ST Patsy	9 Oct 73/00Z	958 mb	80 kts	85 kts
	10 Oct 73/00Z	887 mb	140 kts	147 kts
ST Elsie	11 Oct 75/00Z	972 mb	75 kts	70 kts
	12 Oct 75/00Z	900 mb	135 kts	138 kts
ST June	18 Nov 75/18Z	946 mb	100 kts	98 kts
	19 Nov 75/18Z	877 mb	150 kts	156 kts
ST Therese	12 Jun 76/06Z	979 mb	65 kts	61 kts
	13 Jun 76/06Z	905 mb	130 kts	134 kts
ST Fran	6 Sep 76/06Z	974 mb	65 kts	67 kts
	7 Sep 76/06Z	922 mb	125 kts	120 kts
ST Louise	1 Nov 76/18Z	950 mb	90 kts	94 kts
	2 Nov 76/18Z	905 mb	140 kts	134 kts
T Lucy	2 Dec 77/06Z	980 mb	55 kts	60 kts
	3 Dec 77/06Z	927 mb	110 kts	115 kts
ST Judy	18 Aug 79/00Z	987 mb	55 kts	50 kts
	19 Aug 79/00Z	915 mb	110 kts	126 kts
ST Vera	3 Nov 79/06Z	982 mb	70 kts	57 kts
	4 Nov 79/06Z	NA	140 kts	-------
ST Kim	23 Jul 80/12Z	979 mb	70 kts	61 kts
	24 Jul 80/12Z	916 mb	130 kts	125 kts

Table 4. (Continued) This is a listing of explosive developers from 1973-83. The wind speed changes, that occurred during the explosive development, which are listed in the JTWC Annual Tropical Cyclone Reports, are compared to calculated winds from the original reconnaissance data

Storm Name	Date/Time	Central Pressure	Book Wind	Calculated Wind
T Marge	9 Aug 80/00Z	990 mb	40 kts	46 kts
	10 Aug 80/00Z	944 mb	105 kts	100 kts
ST Wynne	8 Oct 80/00Z	975 mb	70 kts	66 kts
	9 Oct 80/00Z	890 mb	130 kts	128 kts
ST Irma	21 Nov 81/00Z	968 mb	70 kts	74 kts
	22 Nov 81/00Z	NA	125 kts	-------
T Cecil	7 Aug 82/00Z	NA	65 kts	-------
	8 Aug 82/00Z	924 mb	115 kts	118 kts
ST Abby	6 Aug 83/18Z	NA	65 kts	-------
	7 Aug 83/18Z	NA	115 kts	-------

Table 5.--Summary of wind speed changes for the Philippines along with the average amount of time required for each change

	Wind Speed Decrease	Time Length of Decay	Wind Speed Increase	Time Length of Increase
Luzon				
SS	15	15	15	15
Mean	28.3 kts	17.6 hrs	24.0 kts	35.6 hrs
SD	16.2	10.6	10.7	18.4
Other Islands				
SS	15	15	15	15
Mean	30.3 kts	30.0 hrs	28.0 kts	30.4 hrs
SD	23.1	14.5	18.0	16.9

Table 6.--Comparison of technique errors for tropical cyclone intensity changes

	24 hours		48 hours	
	JTWC	H	JTWC	H
Mean:	18.22 kts	11.22 kts	27.32 kts	17.54 kts
SD:	16.23	10.12	19.06	16.97
SS:	90	90	69	69

APPENDIX B

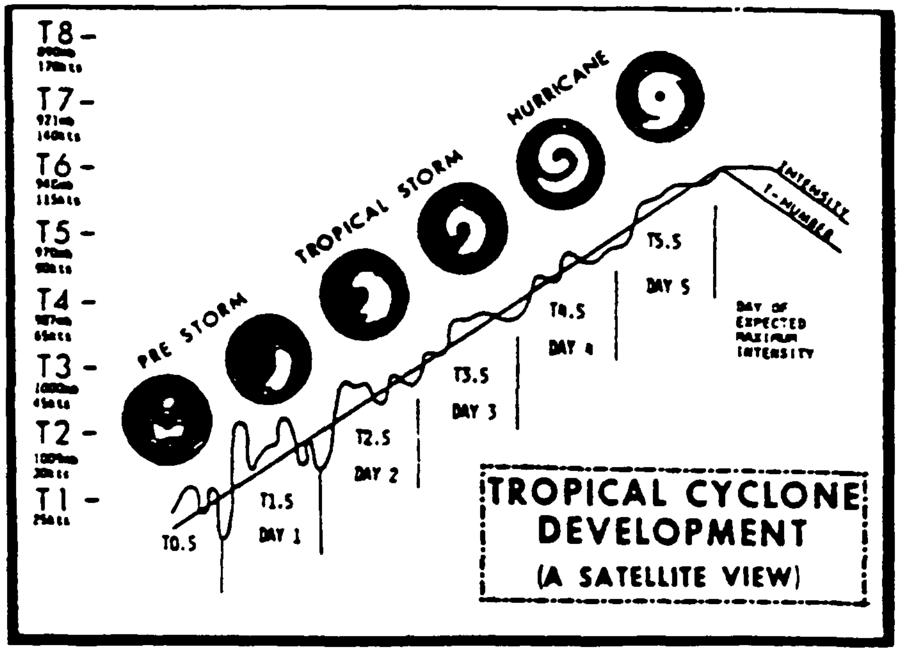


Figure 1. Model of tropical cyclone development used in intensity analysis (after Dvorak, 1984).

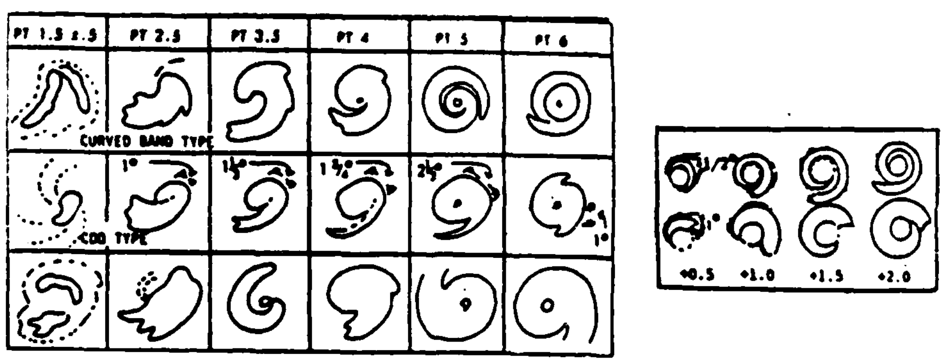


Figure 2. Cloud intensity patterns determined from central and banding features (after Dvorak, 1984).

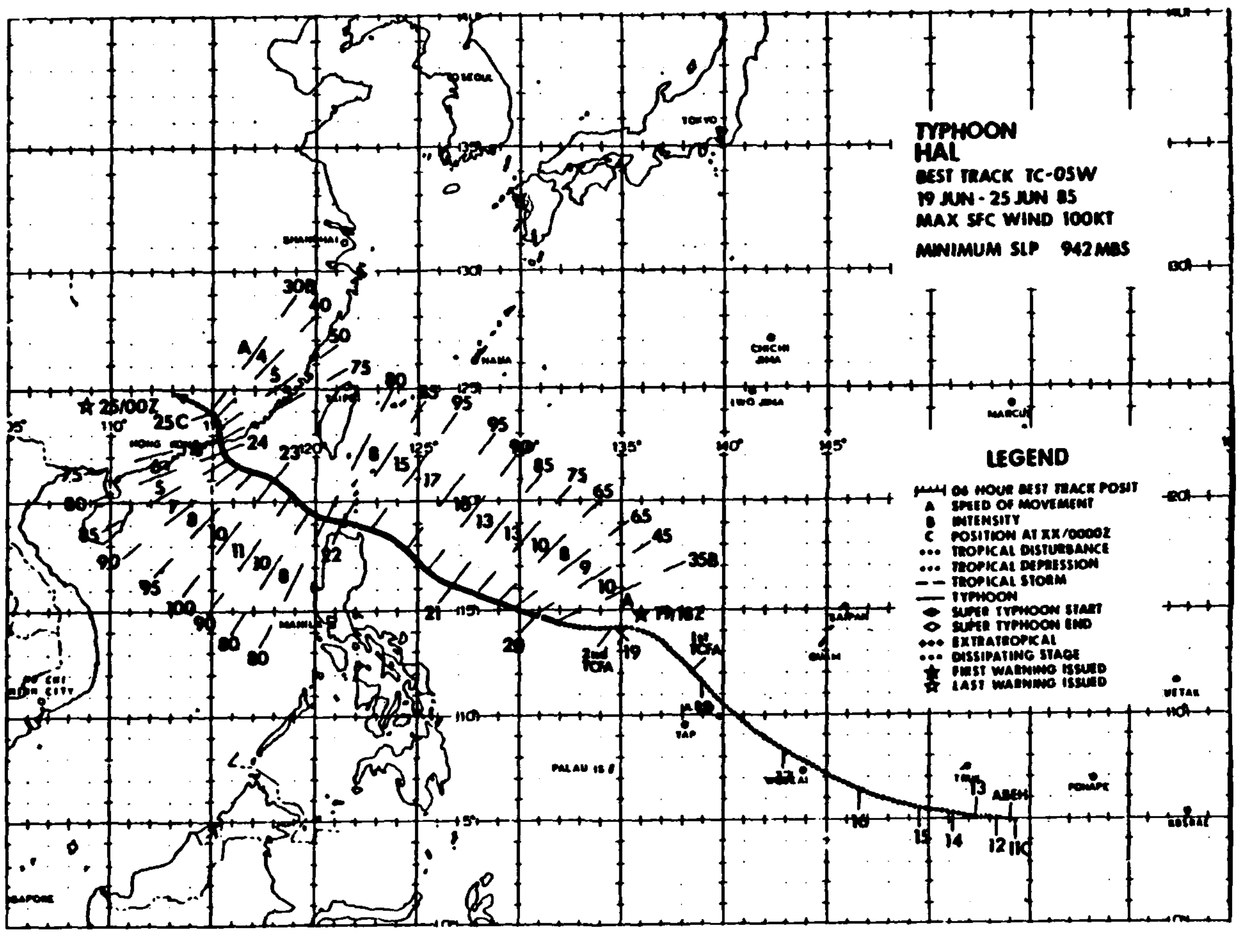


Figure 3. Sample of the gridded storm track plots (after JTWC, 1985).

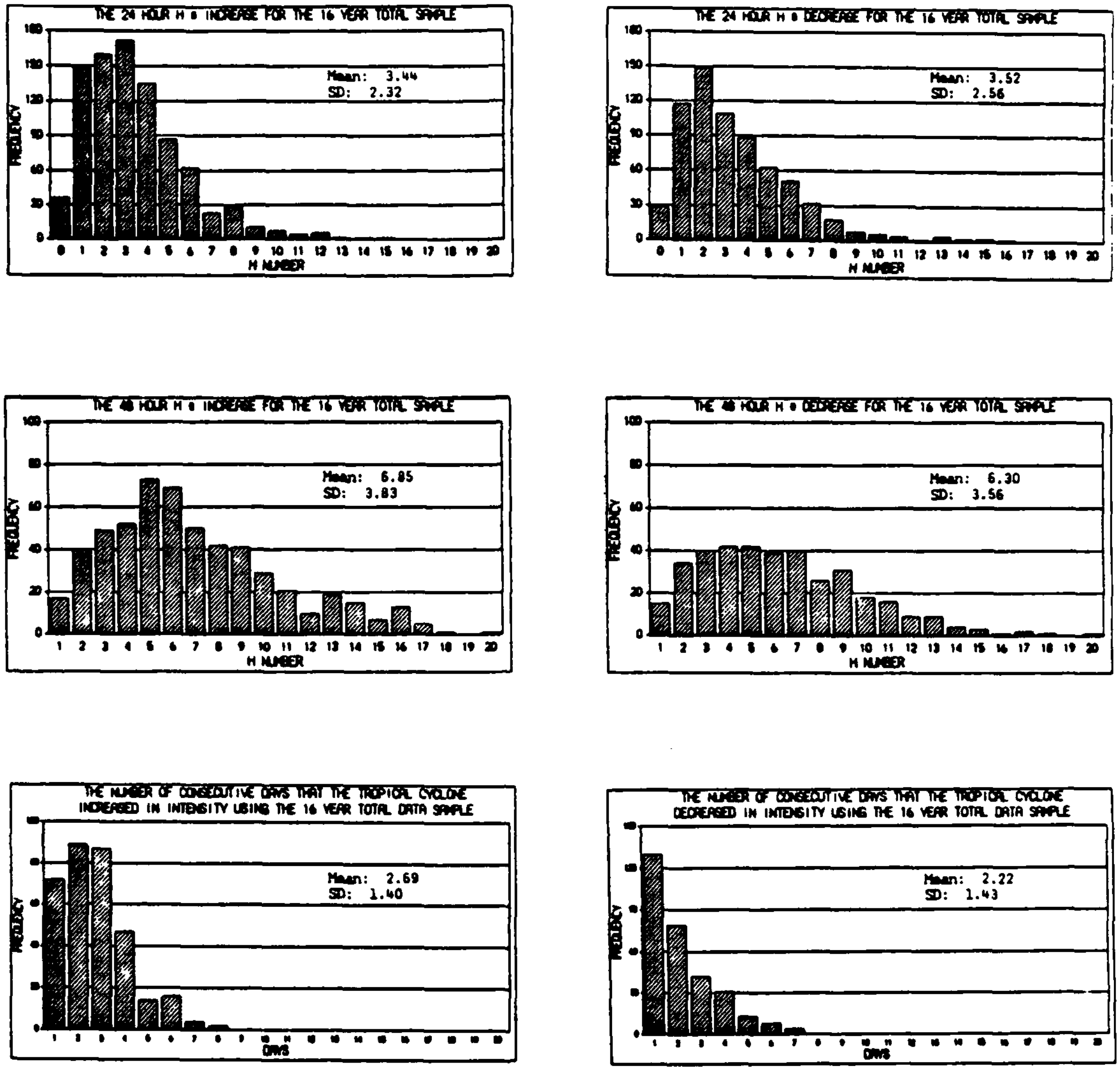


Figure 4. This summary is composed of six bar graphs which show the mode for each category examined (ie. 24 and 48 hour intensity changes and consecutive days for which each occurred) for the total sample. Additionally, the mean and standard deviation are included on each chart.

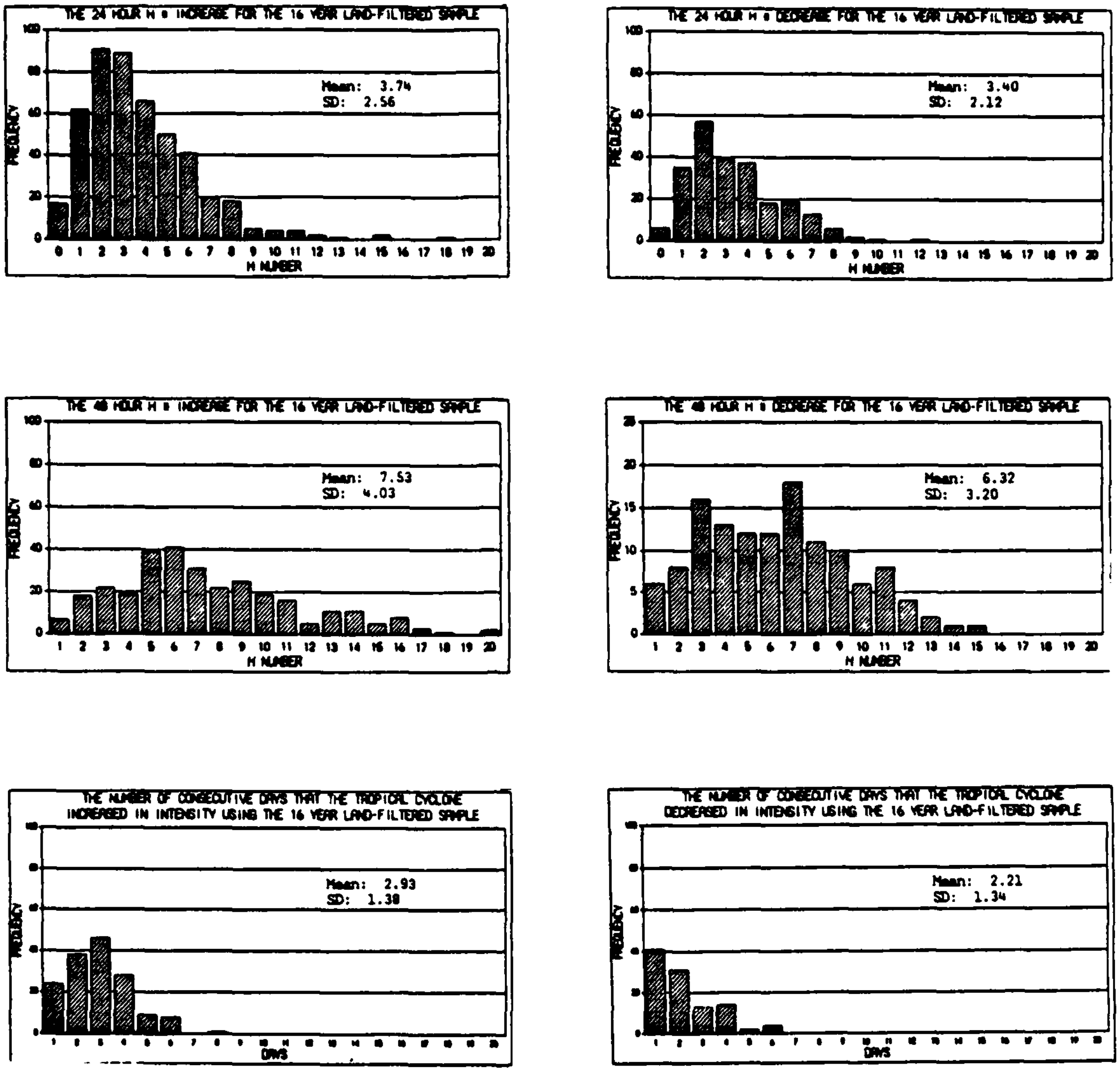


Figure 5. Same as Fig. 4 except for the land-filtered sample.

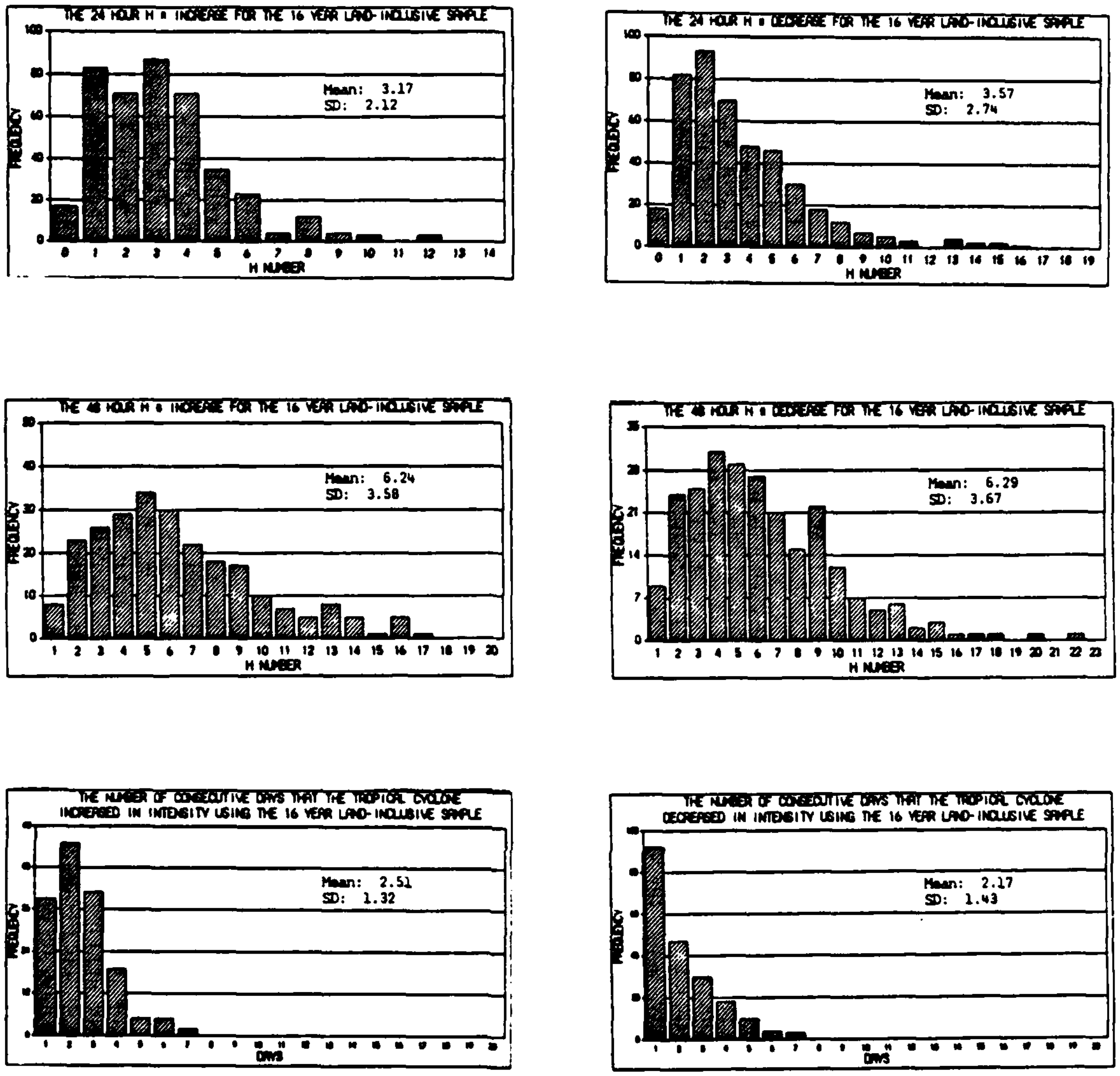


Figure 6. Same as Fig. 4 except for the land-inclusive sample.

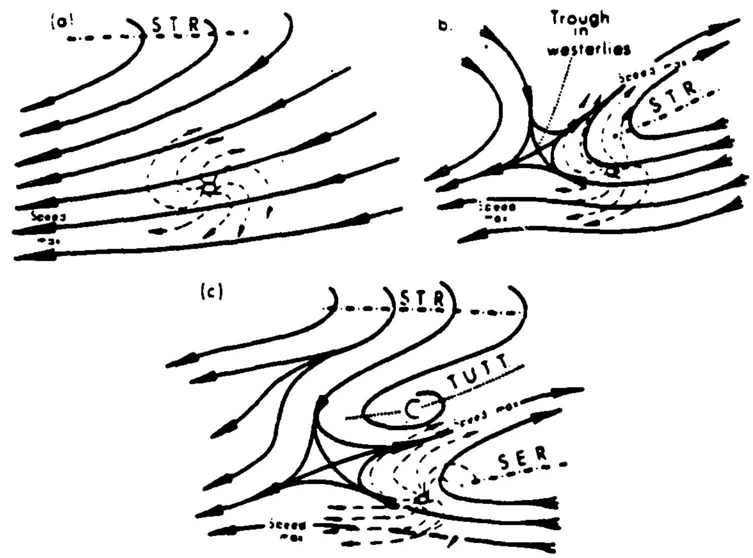


Figure 7. Schematic of storm outflow interaction (dashed lines) with the larger scale, upper-tropospheric circulation (solid lines). STR is the sub-tropical ridge; SER; the sub-equatorial ridge; TUTT, the tropical upper-tropospheric trough (after Sadler, 1976).

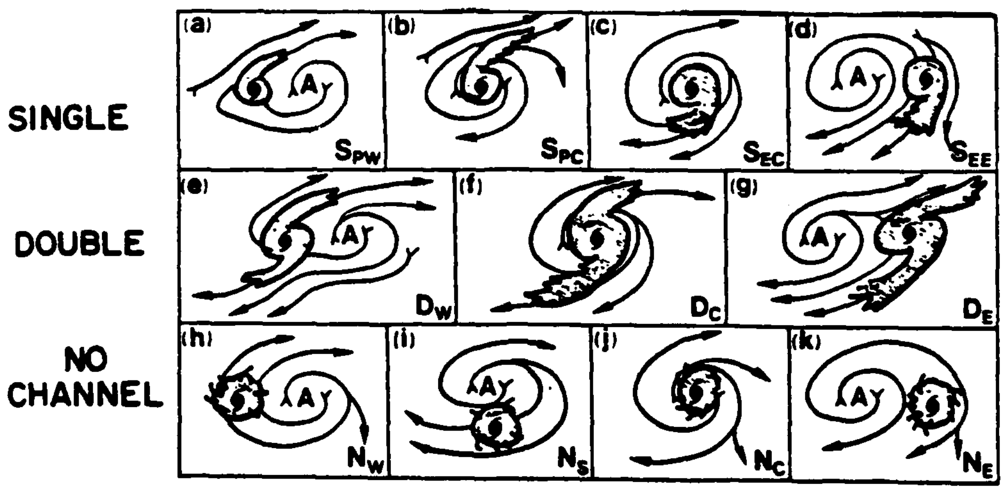


Figure 8. Variety of outflow patterns associated with tropical cyclone intensification for Northern Hemisphere cases (after Chen and Gray, 1985).

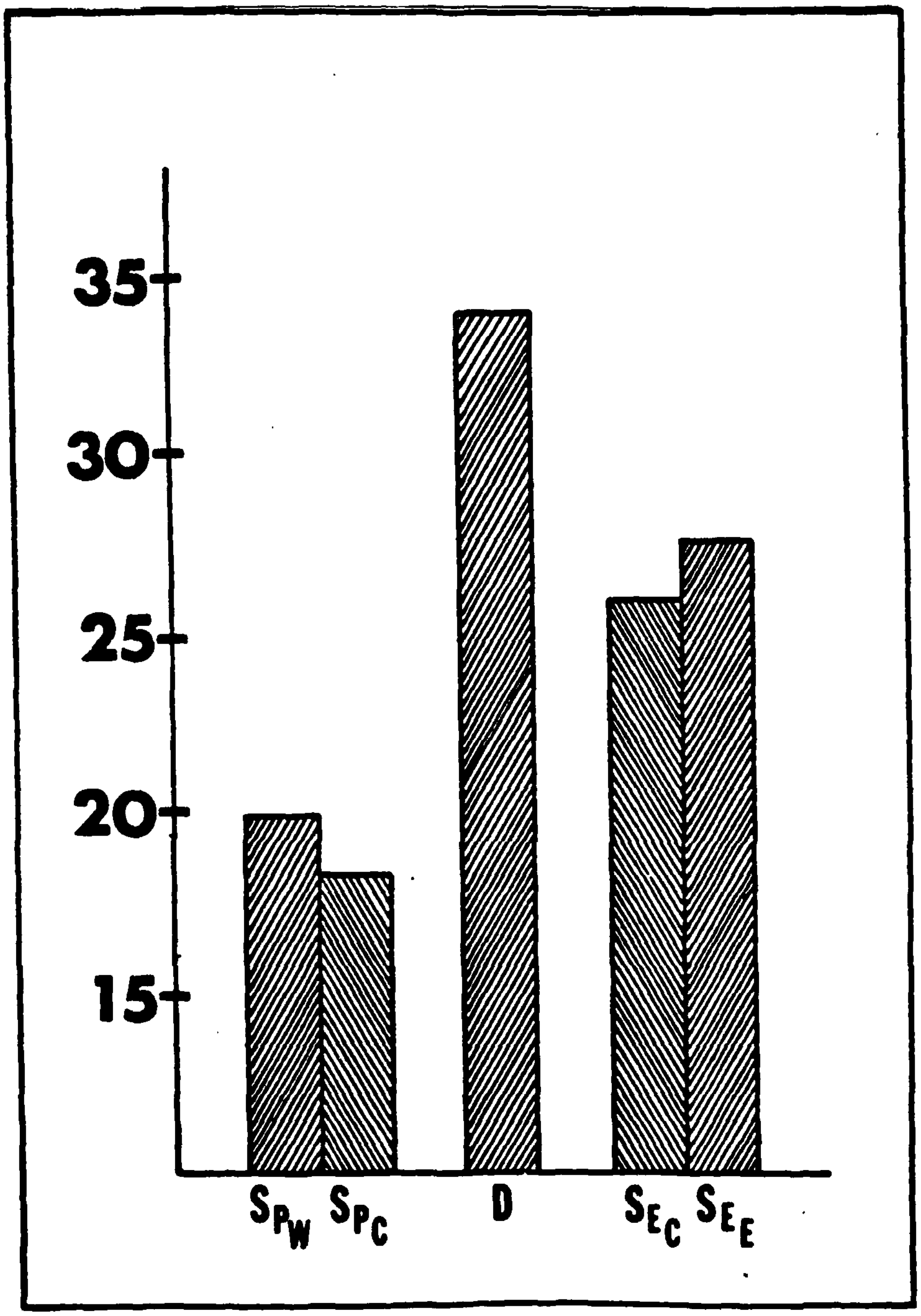


Figure 9. Average maximum wind increase (kts/6 hours) associated with different outflow patterns (after Chen and Gray, 1985).

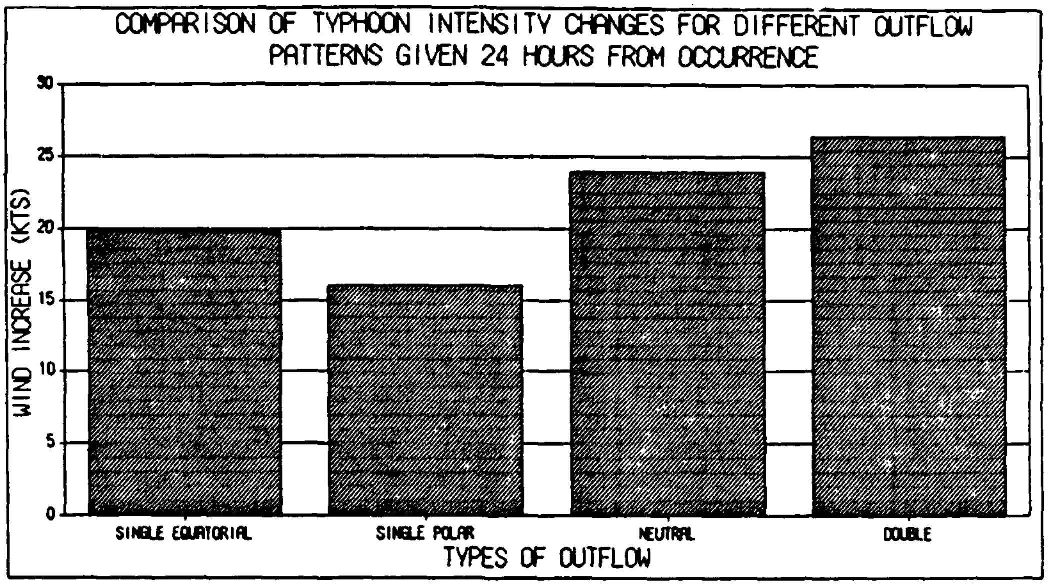


Figure 10. Comparison of intensity changes for different outflow patterns averaged over a seven year period.

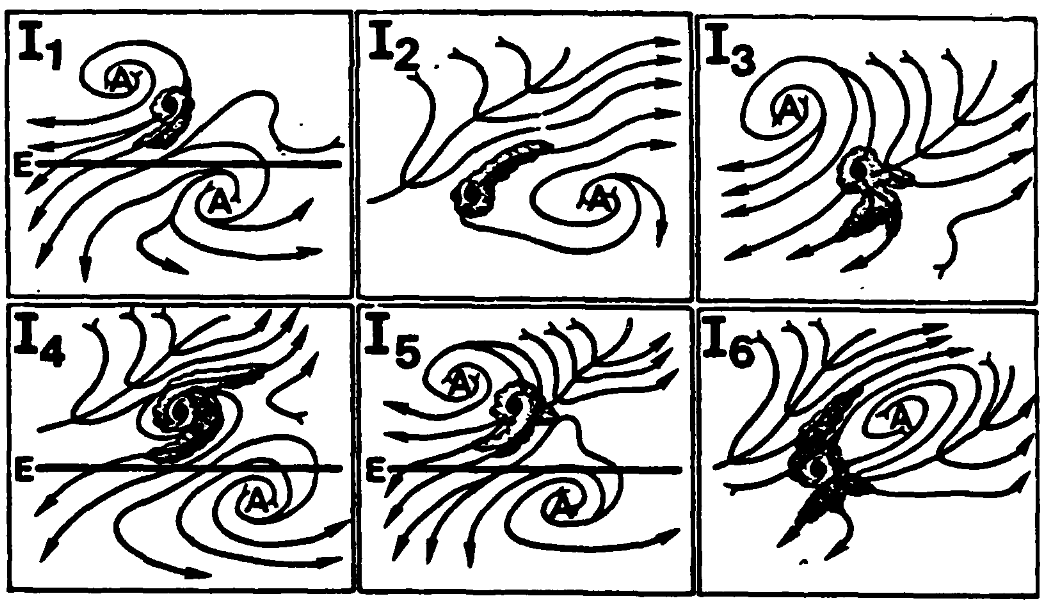


Figure 11. Six types of interactions between a tropical cyclone and its surroundings (after Chen and Gray, 1985).

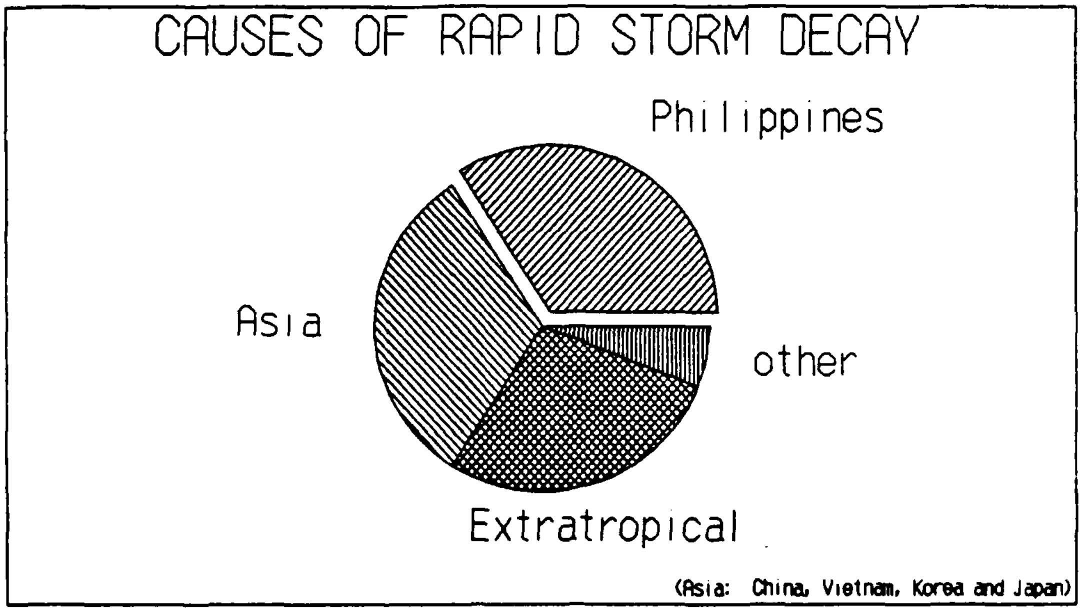


Figure 12. Depiction of causes which lead to rapid decay of Northwestern Pacific tropical cyclones.

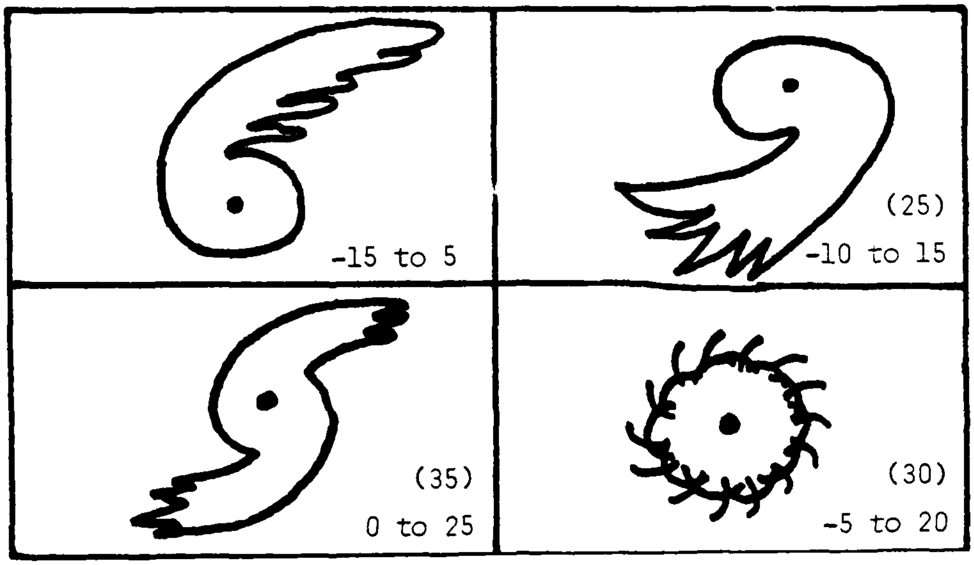
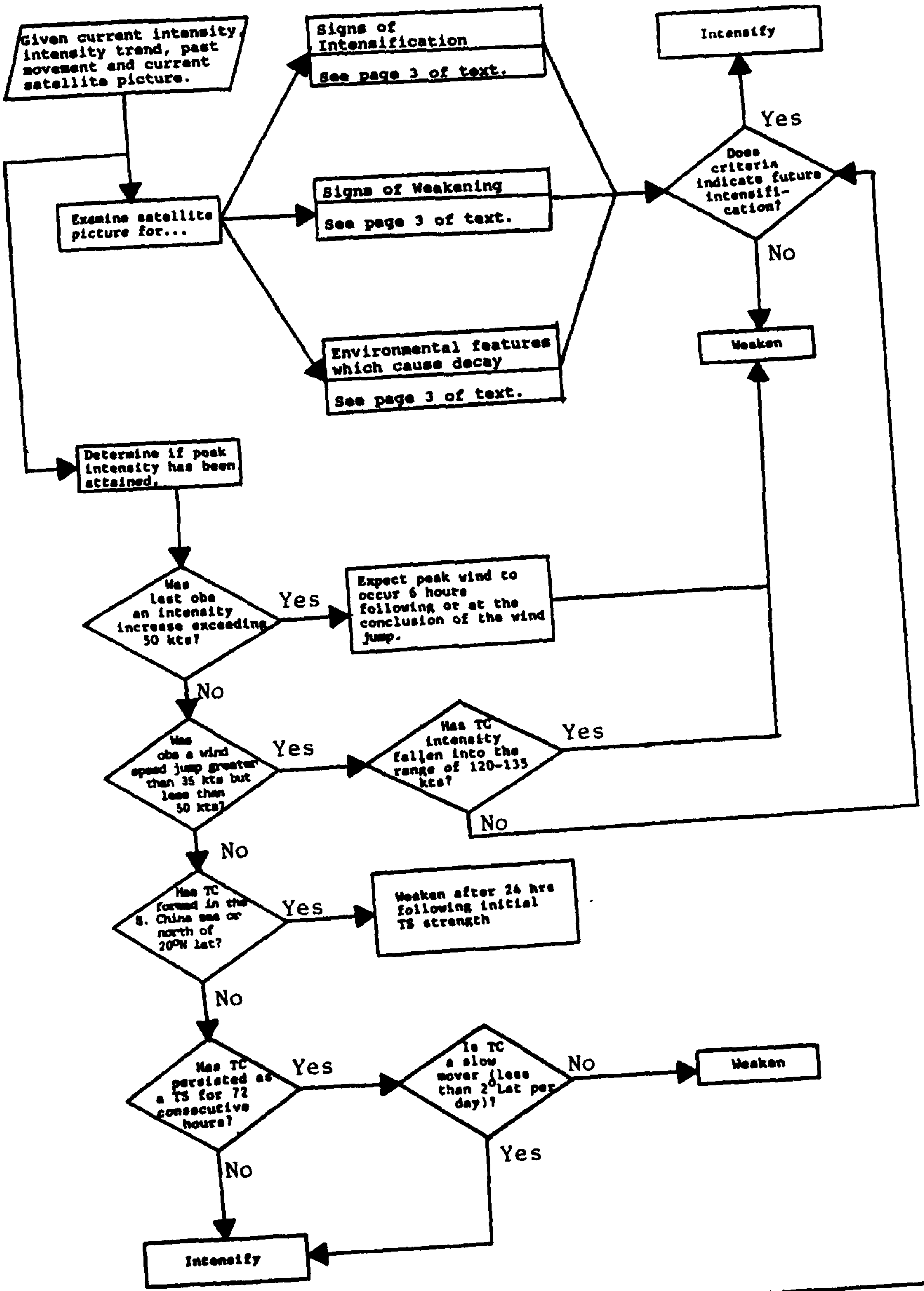
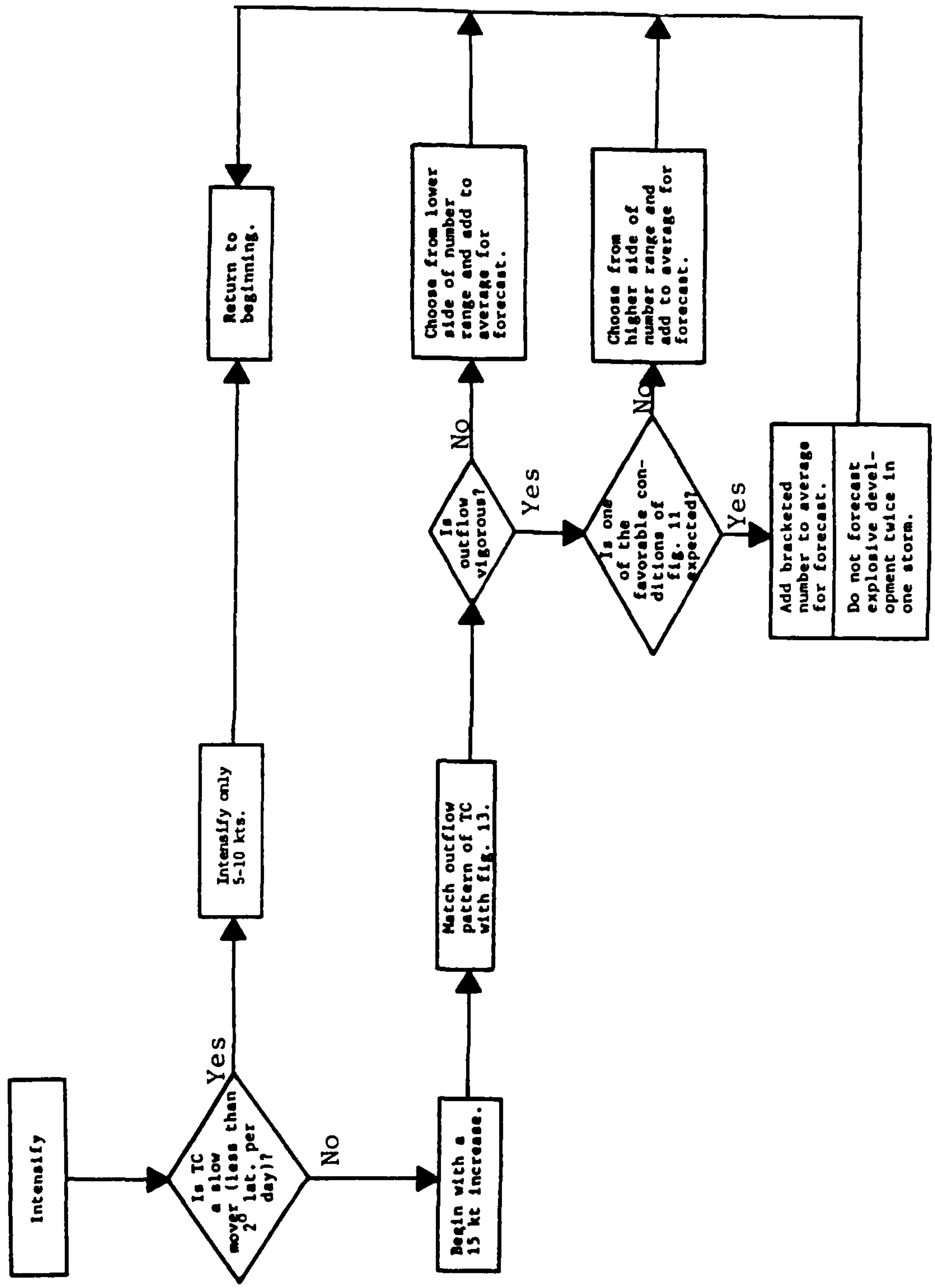


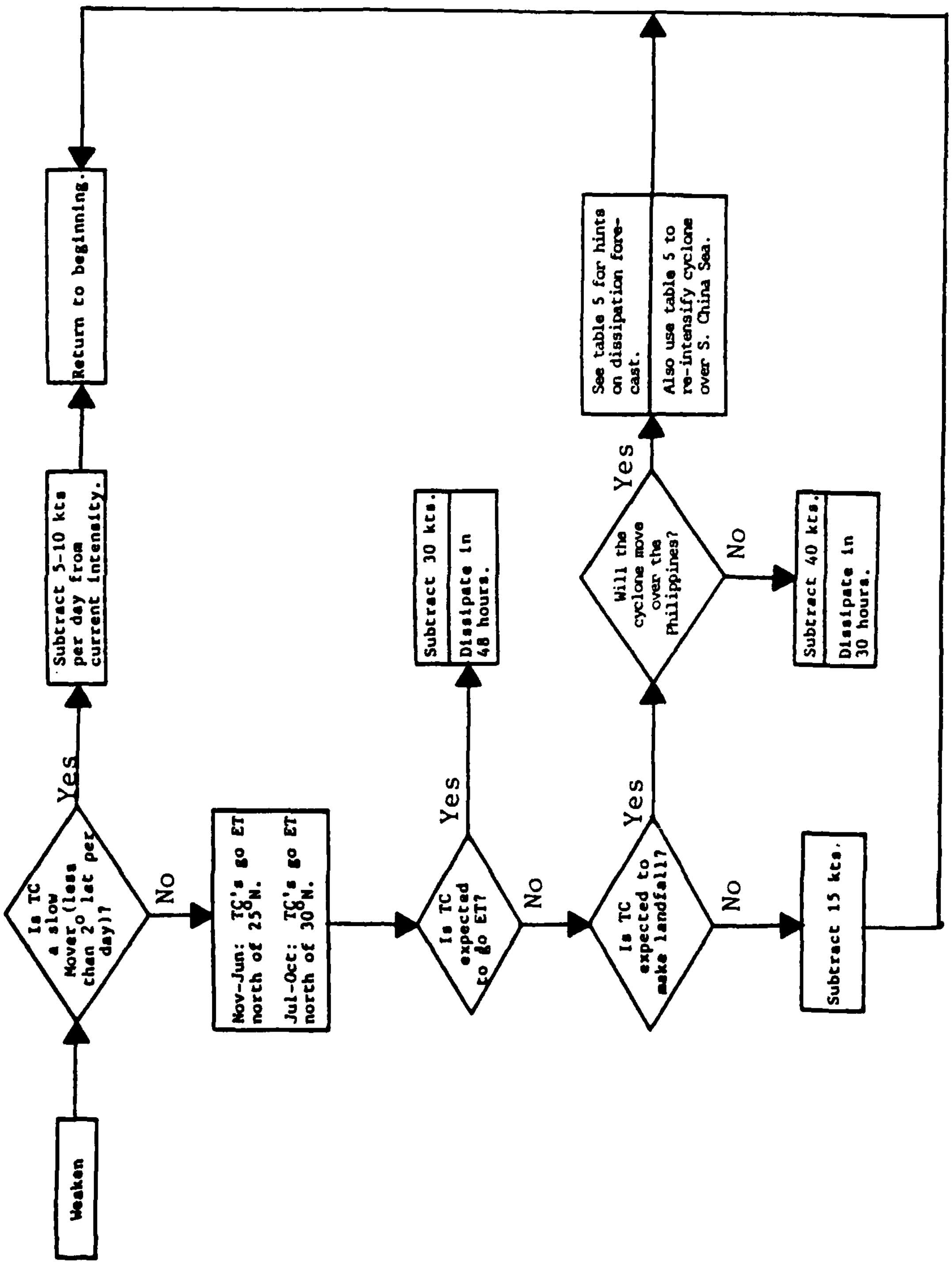
Figure 13. Examples of different tropical cyclone outflow patterns. The number range and bracketed numbers are used to indicate possible values of intensity change (added to 15 kts) in a 24 hour period, depending on the strength of the outflow (modified from Chen and Gray, 1985).

APPENDIX C

FORECAST FLOW CHART




Intensify
Is TC a slow mover (less than 2° lat. per day)?
Yes
No
Intensify only 5-10 kts.
Return to beginning.
Begin with a 15 kt increase.
Match outflow pattern of TC with fig. 13.
Is outflow vigorous?
No
Yes
Choose from lower side of number range and add to average for forecast.
Is one of the favorable conditions of fig. 11 expected?
No
Yes
Choose from higher side of number range and add to average for forecast.
Add bracketed number to average for forecast.
Do not forecast explosive development twice in one storm.


Weaken
Is TC a slow mover (less than 2° lat per day)?
Yes
No
Subtract 5-10 kts per day from current intensity.
Return to beginning.
Nov-Jun: TC's go ET north of 25°N.
Jul-Oct: TC's go ET north of 30°N.
Is TC expected to go ET?
Yes
No
Subtract 30 kts.
Dissipate in 48 hours.
Is TC expected to make landfall?
Yes
No
Will the cyclone move over the Philippines?
Yes
No
See table 5 for hints on dissipation forecast.
Also use table 5 to re-intensify cyclone over S. China Sea.
Subtract 40 kts.
Dissipate in 30 hours.
Subtract 15 kts.

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